Recipes for writing algorithms to retrieve columnar water vapor for 3-band multi-spectral data

Christoph C. Borel, Karen L. Hirsch and Lee K. Balick
Space and Remote Sensing Sciences Group
Mailstop C 323, Los Alamos National Laboratory
Los Alamos, NM 87545, USA
E-mail : cborel@lanl.gov WEB: http://nis-www.lanl.gov/~borel/
(505)-667-8972 FAX (505)-667-3815

Contents

1. Introduction
2. Transmission based CIBR recipe
3. Radiance based CIBR recipe
4. APDA recipe
5. Comparison of results
6. Conclusions
7. Acknowledgments

Introduction

Water vapor retrievals have four following steps in common:

1. Run a radiative transfer (RT) algorithm for a range of water vapor values and a particular observation geometry,
2. Compute sensor band-averaged radiances,
3. Compute a non-linear fit of channel ratios (e.g. CIBR or APDA) as a function of water vapor,
4. Apply the inverse fit to retrieve columnar water vapor as a function of channel ratio.

Transmission based CIBR recipe

Total spectral attenuation due to water vapor alone is given by:

$$T_{H2O}(\nu, CW) = T_{\mathrm{H2O,sun}\rightarrow\mathrm{ground}}(\nu, CW)\ \ T_{\mathrm{H2O,ground}\rightarrow\mathrm{sensor}}(\nu, CW), \qquad (1)$$

where ν is the wavenumber in cm^{-1} and CW is the columnar water vapor in g/cm^2.

The steps for CIBR retrieval are:

1. The default *TAPE5* for MODTRAN4 was:

```
T    a     2     0     0     0     0     0     0     0     0     0     0     0    0.001    0.00
F    0T    2    355.000  Gb.bb
     1     0     0     0     0     0      0.000      0.000      0.000      0.000      0.000
   ccc.ccc     d.ddd 0.000    eee.eee      0.000      0.000      0.000     0
    0.8000     1.1000     0.0100     0.0200             M   A
    0
```

where:

Atmosphere type: $a =$ 1=Tropical Atmosphere, 2=Midlatitude Summer, 3=Midlatitude Winter, 4=Subarctic Summer, 5=Subarctic Winter, 6=1976 US Standard,

Water vapor: $b.bb =$ 0.05, 0.1, 0.2, 0.3, .5, 0.75, 1., 1.25, 1.5, 1.75, 2., 2.5, 3., 3.5, 4., 4.5, 5., 6., 6.5, 7. and 8. g/cm^2,

Sensor height: $ccc.ccc =$ 100.00 km,

Ground altitude: $d.ddd =$ read from data base

Phase angle: $eee.eee = 180^o - \theta$ where θ is either the sun or view zenith angle.

2. Run MODTRAN4 in transmission mode and read transmission from TAPE7 and compute band-averaged transmission $T_{i,H2O}(CW)$:

$$T_{i,H2O}(CW) = \frac{\int_{\nu(i)_a}^{\nu(i)_b} R_i(\nu) T_{H2O}(\nu, CW) d\nu}{\int_{\nu(i)_a}^{\nu(i)_b} R_i(\nu) d\nu}, \tag{2}$$

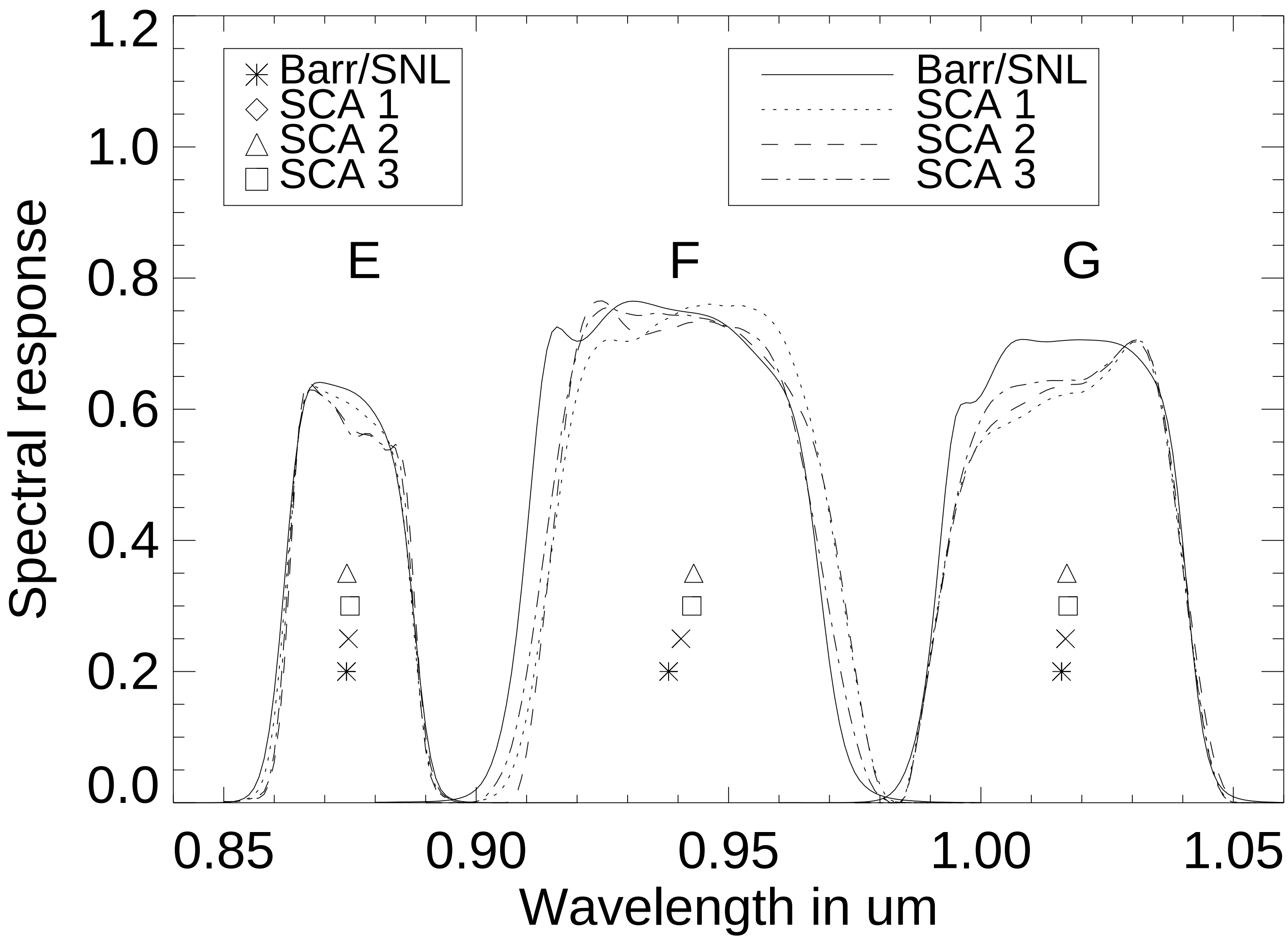
where $R_i(\nu)$ is the spectral response of the i-th channel, $i = \{E,\ F,\ G\}$.

Two types of spectral responses are used for MTI:

(a) Barr/SNL: filter transmissions measures at room temperature & nadir and converted by SNL model to off-nadir cones of $f = 3.5$ telescope at 75^o K.

(b) LANL measured dual monochromator spectral responses (new).

For MTI spectral responses for water vapor channels E, F and G are:



Center wavelengths $\lambda_{c,i}$ with:

$$\lambda_{c,i} = \frac{10000}{\nu_{c,i}}, \quad \text{where} \quad \nu_{\mathrm{c,i}} = \frac{\int_{\lambda(\mathrm{i})_\mathrm{a}}^{\lambda(\mathrm{i})_\mathrm{b}} \lambda \mathrm{R_i}(\lambda)\mathrm{d}\lambda}{\int_{\lambda(\mathrm{i})_\mathrm{a}}^{\lambda(\mathrm{i})_\mathrm{b}} \mathrm{R_i}(\lambda)\mathrm{d}\lambda}. \tag{3}$$

- The center wavelengths for the Barr/SNL filter functions are: $\lambda_{c,E} = 0.874310\mu m$, $\lambda_{c,F} = 0.93813\mu m$ and $\lambda_{c,G} = 1.01599\mu m$.
- The bandwidths for the Barr/SNL filter functions are $BW_E = 0.0160052\mu m$, $BW_F = 0.0428301\mu m$ and $BW_G = 0.0340523\mu m$.

CIBR look-up-table construction:

$$CIBR_{RT} = \frac{T_{F,H2O}(CW_{RT})}{w_1 T_{E,H2O}(CW_{RT}) + w_2 T_{G,H2O}(CW_{RT})} \tag{4}$$

Interpolation scheme:

$$x = \sqrt{CW_{RT}} \quad \text{and} \quad \mathrm{y} = \log_{10}[\mathrm{CIBR_{RT}}(\mathrm{CW_{RT}})]. \tag{5}$$

Using a linear fit $Q(z) = a_0 + a_1 z$ to the pair (x, y) we can now generate a continuous LUT with $CW_{RT} = x^2$ and $CIBR_{RT} = 10^{Q(CW_{RT})}$.

3. To compute the CIBR from MTI data we use band-averaged radiance values L_i in the following expression (for detailed derivations see Schläpfer et al, (1996)):

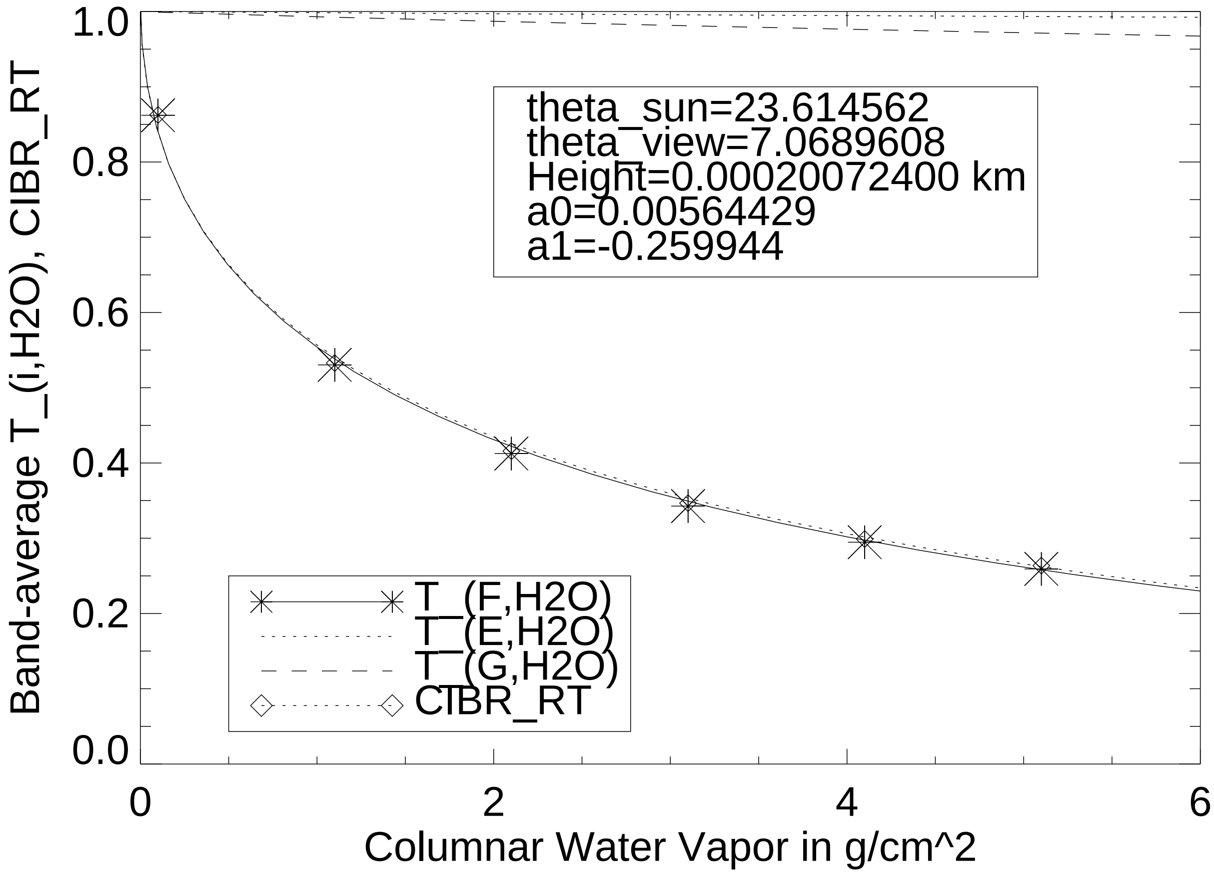
$$CIBR_{data} = \frac{L_F}{w_1 L_E + w_2 L_G}, \quad \text{where} \tag{6}$$

where:

$$w_1 = \frac{\lambda_{c,G} - \lambda_{c,F}}{\lambda_G - \lambda_E} \quad \text{and} \quad \mathrm{w}_2 = \frac{\lambda_{\mathrm{c,F}} - \lambda_{\mathrm{c,E}}}{\lambda_{\mathrm{G}} - \lambda_{\mathrm{E}}}.$$

For MTI using the Barr/SNL filter functions we have $w_1 = 0.5495$ and $w_2 = 0.4505$.

Example of fitting the band-averaged water vapor transmissions $T_{i,H2O}(CW_{RT})$ and $CIBR_{RT}(CW_{RT})$ for a MTI data set:



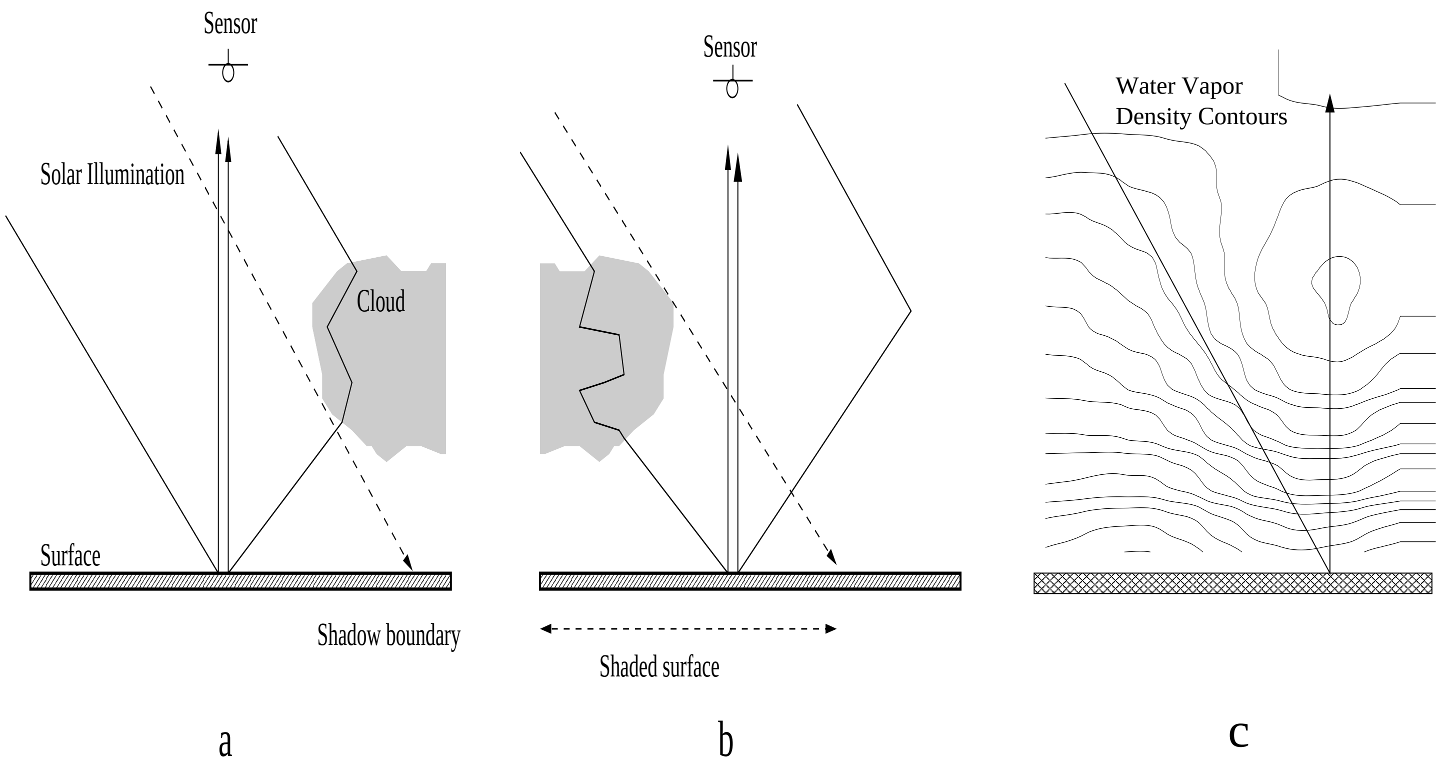
4. To compute the columnar water vapor CW_{data} from $CIBR_{data}$ the following inverse function is used:

$$CW_{data} = [P(\log_{10}(CIBR_{data}))]^2, \tag{7}$$

where $P(z) = b_0 + b_1 z$ is a linear fit to $x = \log_{10}[CIBR_{RT}(CW_{RT})]$ and $y = \sqrt{CW_{RT}}$.

The advantages of this method are:

1. Simpler to implement and much faster to run than radiance based CIBR.
2. In principle can handle cases:
   (a) The surface receives direct sunlight and light scattered from the side of a cloud.
   (b) The surface is in a cloud shadow and we receive light scattered through the cloud.
   (c) The atmosphere is not horizontally homogeneous, e.g. devise a retrieval where the water vapor profiles are iteratively adjusted for both paths.



Radiance based CIBR recipe

1. Run MODTRAN4 in radiance mode for a specific CW_{RT}, atmosphere (tropical, mid-latitude summer, mid-latitude winter, sub-arctic summer, sub-arctic winter) and aerosol model (rural, maritime or urban). The visibility was set to 23 km and the surface reflectance to 0.45. The multiple scattering code used is the two-stream Isaacs method.

   Calculate $CIBR_{RT}(CW_{RT})$ using the instrument specific response functions $R_i(\nu)$:

   $$CIBR_{RT}(CW_{RT}) = \frac{L_F}{w_1 L_E + w_2 L_G}, \quad \text{where} \;\; \mathrm{L_i} = \frac{\int_{\nu(\mathrm{i})_\mathrm{a}}^{\nu(\mathrm{i})_\mathrm{b}} \mathrm{R}(\nu)\mathrm{L}(\nu)\mathrm{d}\nu}{\int_{\nu(\mathrm{i})_\mathrm{a}}^{\nu(\mathrm{i})_\mathrm{b}} \mathrm{R_i}(\nu)\mathrm{d}\nu}, \tag{8}$$

   where $L(\nu)$ is obtained from MODTRAN TAPE7.

2. Repeat 1 for 10 times to create a look-up table of equally spaced $[CW_{RT}, CIBR(CW_{RT})]$ from a minimum to a maximum value of CW_{RT}.

3. For each pixel calculate $CIBR_{data}$ ratio from sensor data using eq (8) where the measured radiances are used in L_F, L_E and L_G.

4. For each pixel interpolate $CIBR_{data}$ to determine the appropriate CW for that pixel from the look-up-table $[CW_{RT}, CIBR_{RT}(CW_{RT})]$.

APDA recipe

In contrast to CIBR, APDA corrects for path radiance in the absorption band by using MODTRAN4 determined path radiance as a function of water vapor column amount.

Basic principle: Iterate between two coupled equations, one based on a 3-channel ratio and the other on a function $f_{RT}()$ to convert the ratio into columnar water vapor:

$$\begin{aligned} APDA_{data} &= \frac{L_{F,data} - L_{F,Path,RT}(CW_{data})}{w_1(L_{E,data} - L_{E,Path,RT}) + w_2(L_{G,data} - L_{G,Path,RT})} \\ CW_{data} &= f_{RT}(APDA_{data}) \end{aligned} \tag{9}$$

where:

- $L_{F,Path}(CW_{data}) = c_0 + c_1 CW_{data} + c_2 CW_{data}^2$ is a second order polynomial fit to the values of $L_{F,Path}$ as a function of CW_{RT} calculated from MODTRAN4.
- $L_{E,Path}$ and $L_{G,Path}$ are assumed to be water vapor independent, due to their position outside the water vapor feature at 940nm.

Notes:

- $APDA_{RT}$ is derived using band averaged radiance values from MODTRAN4 run $\rho_{surface} = 0.45$ as a function of CW_{RT}.
- This $APDA_{RT}(CW_{RT})$ is interpolated so that a CW_{data} value is returned for each value of $APDA_{data}$.

APDA procedure steps:

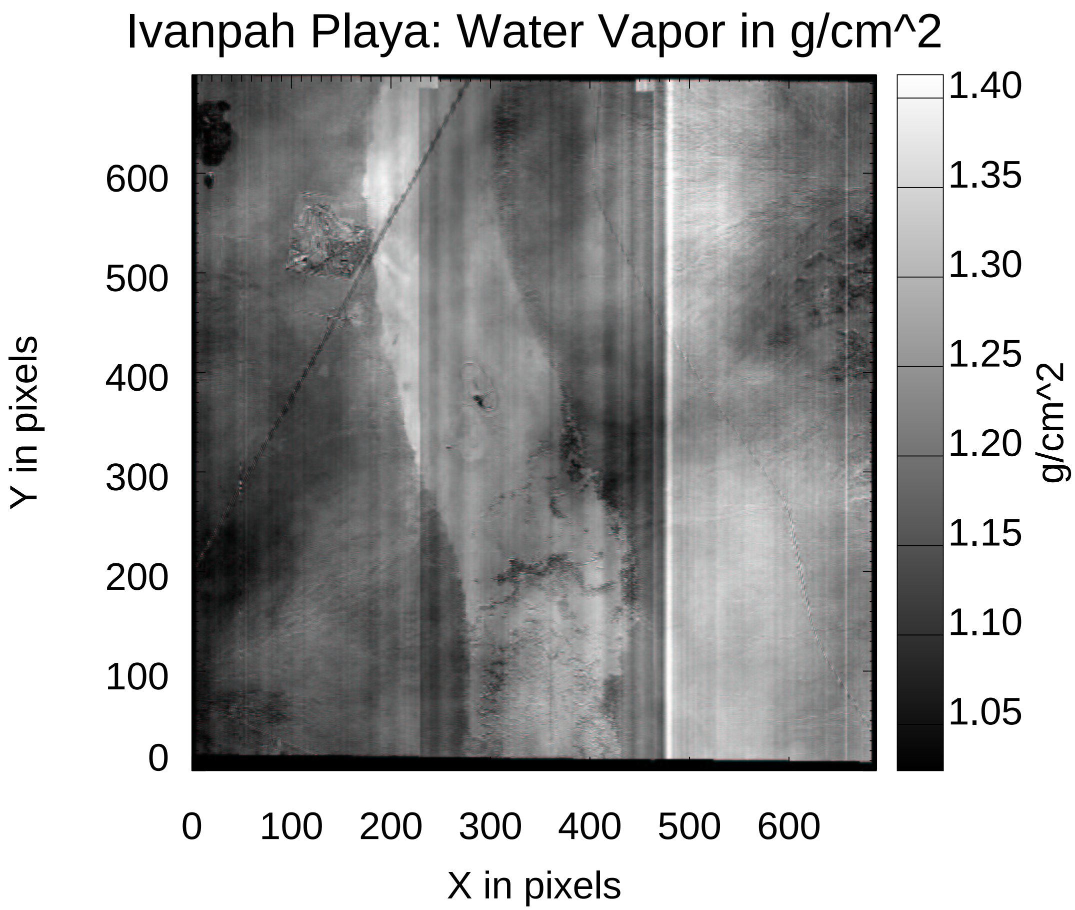
1. Run MODTRAN4 for a value of CW_{RT}.
2. Compute L_i and $L_{i,Path}(\nu)$ by convolving the top of atmosphere radiance $L(\nu)$ and path radiance $L_{Path}(\nu)$ values with response functions $R_i(\nu)$ for $i = \{E, F, G\}$.
3. Repeat 1 and 2 to create $L_E(CW)$, $L_F(CW)$, $L_G(CW)$, $L_{E,Path}$, $L_{F,Path}(CW)$, and $L_{G,Path}$.
4. Create a lookup table $[CW_{RT}, APDA_{RT}(CW_{RT})]$.
5. Create a quadratic fit to the look-up table $[CW_{RT}, L_{F,Path}(CW_{RT})$.
6. Using eq (10) calculate $APDA_{data}$ for an initial value of CW_{data}, e.g. the neighbor pixel.
7. Find CW_{data} value from $f_{RT}(APDA_{RT}(CW_{data})$
8. Convergence is achieved when the previous estimated CW_{data} value is within 1×10^{-3} of the current value. Otherwise, iterate, so that the new CW_{data} becomes the previous estimated CW_{data} value.

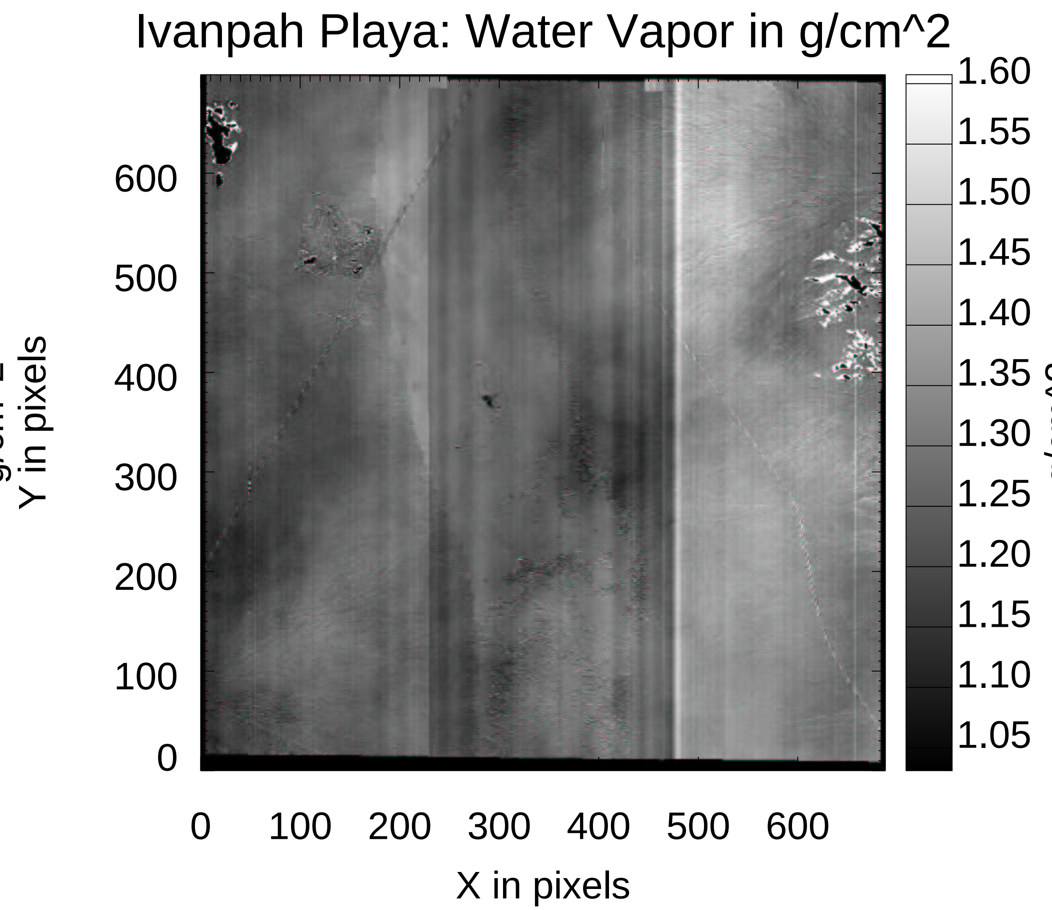
Notes:

1. Typically 3 iterations are sufficient to converge.
2. Need good information on aerosols (aerosol type and optical depth).
3. Sub-pixel registration errors cause erroneous values near water-land boundaries

Comparison of results: for details see paper by Hirsch et al, 2001

Ivanpah Playa in Nevada for September 15, 2000. The sun-photometer measured water vapor amount was 1.35 g/cm^2





Note: Boundary between bright playa and surounding area disapears in APDA.

Conclusions

- The transmission based CIBR reports higher values than the radiance based algorithm.
- Described first automated implementation of APDA for MTI.
- APDA performs much better over dark targets than CIBR when aerosol properties known.

Acknowledgements

Many people at:

- Los Alamos National Laboratory (P. Weber, J. Szymanski, P. McLachlan,...)
- Sandia National Laboratories,
- Savannah River Technological Center, and
- Partners in industry and academia

Financial support:DOE W-7405-ENG-36